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SOME FACTORS INFLUENCING THE PERFORMANCE OF DIAPHRAGM INDICATORS OF EXPLOSION PRESSURES

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ABSTRACT

Information obtained during the development and use of accurate diaphragm-type indicators of the pressures developed during explosions of gaseous mixtures in bombs is presented. Although some of the following conclusions are not original, all are supported by new experimental evidence.

It is shown that all passages and cavities on the explosion side of the diaphragm should be eliminated for highest accuracy. Although the sensitivity of the diaphragm to pressure difference must not be less than the value determined by the accuracy with which pressures are to be measured, it is important when highest accuracy is desired, that the sensitivity shall not greatly exceed this same value so that the inertia error will not become larger than the allowable tolerance. Radial tension in the diaphragm is advantageous in reducing time lag. A blued or polished surface is preferable to one which absorbs more radiant energy. Projections around the diaphragms are without measurable effect upon the performance of the indicators. It seems probable that, with a properly designed indicator, the measured values of explosion pressure need not deviate from the actual pressure by more than a few tenths of 1 mm Hg.

CONTENTS

I. INTRODUCTION

Experimental determinations of a number of the burning characteristics of various gaseous mixtures, when exploded in a spherical bomb, have been described in a recent publication.[1] In order to

[1] E. F. Fiock, C. F. Marvin, Jr., F. R. Caldwell, and C. H. Roeder; *Flame speeds and energy considerations for explosions in a spherical bomb*, Technical Report No. 682, National Advisory Committee for Aeronautics, 1940.

make the results reliable over a wide range of conditions, it was necessary that the measurements of pressure be accurate, both in the early stages of the burning and later in the combustion process when the pressures were high and rising rapidly. A diaphragm-type indicator, which shows when a definite pressure is reached, was selected for these measurements because of its inherent simplicity, adaptability, and high precision. However, preliminary experiments were necessary to determine the most favorable dimensions and the most suitable methods of mounting and of recording.

It seemed simpler, mechanically, to mount the pressure indicators completely outside the spherical bomb, and the presence of perforated disks to support the diaphragms on the explosion side appeared to offer some advantages. Hence, preliminary experimental studies of the effects of the necessary passages and of backing disks were undertaken prior to designing the spherical bomb and its pressure indicators. The results of these preliminary studies may be of practical importance, since diaphragm indicators used for measuring explosion pressures in engine cylinders have frequently had either connecting passages or backing disks, or both.

The present results thus fall logically into two groups. The first of these was obtained with special indicators having soft diaphragms of rolled silver, designed to show the effects of restrictions between the flame and the diaphragm and used at either end of a cylindrical bomb designed for test purposes. The second group was obtained with indicators having their spring-steel diaphragms directly exposed to the explosive charge in a spherical bomb.

II. EXPERIMENTS WITH INDICATORS ON A TEST BOMB

1. TEST APPARATUS

The apparatus used in testing preliminary forms of the indicators is shown diagrammatically in figure 1. It provided for the comparison of two indicators differing from each other in only one significant constructional detail, and for the investigation of a number of design features through simple mechanical changes.

One indicator was mounted at each end of the cylindrical bomb, so that both indicators were subjected to the same rise in pressure. The figure shows indicators of the balanced-diaphragm type, in which a very flexible circular diaphragm was clamped at the rim between two perforated supporting disks. For brevity, the supporting disk on the explosion side will be referred to as the inner backing disk and that on the other side of the diaphragm as the outer backing disk.

The number and pattern of the perforations differed for the inner backing disks, as did the thickness. To provide for the necessary movement of the diaphragms, the adjacent surfaces of the inner disks were shaped as cones having approximately 0.004-in. altitude.

In all cases the outer backing disks were alike, having both surfaces plane and normal to the axes and perforated in the pattern illustrated with diaphragm *A* of figures 3, 4, and 5. Each had 442 holes, 1.5 mm in diameter, with centers 2 mm apart, and a ring of 6 holes, 1 mm in diameter, around a central hole 2 mm in diameter through which the end of the insulated electrode passed.

The electrode, shown diagrammatically in figure 1, was of stainless steel, with a rounded and polished contact. It was threaded through

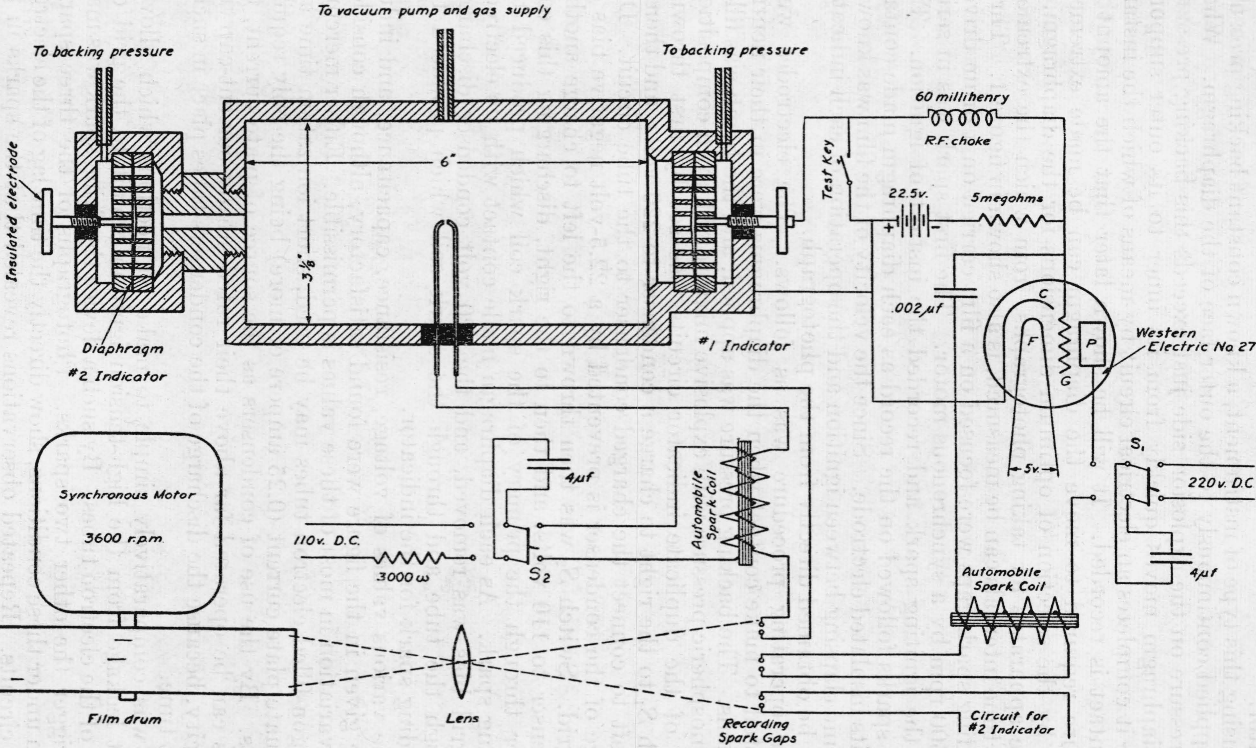

FIGURE 1.—*Diagrammatic representation of cylindrical bomb and recording system.*

a gland which was insulated with mica from the remainder of the indicator.

In using this type of instrument, a known constant backing pressure was applied continuously to the outer face of the diaphragm. When the pressure on the explosion side just exceeds this backing pressure, the diaphragm moves quickly from its inner to its outer support, where it completes an electrical circuit by means of which the instant of contact is recorded. It will be shown later that the amount of pressure required to move the diaphragm can be made extremely small by the selection of optimum dimensions for the diaphragm.

The apparatus for taking photographs, from which the extremely small time intervals can be measured, is also shown in figure 1. Three recording spark gaps were focused on a film carried on a drum driven at 3,600 rpm by a synchronous motor. The first spark was in series with the igniting spark and recorded the instant of ignition. The other sparks followed on the record as each diaphragm made contact with its insulated electrode. Since the velocity of the film was known, the time elapsing between ignition and the operation of each indicator could be obtained directly from the photograph.

The operating procedure was as follows. The electrodes were adjusted to make contact when the diaphragms were in their neutral positions. The backing pressure was applied, and the bomb was filled to atmospheric pressure with explosive mixture of known composition. Each of the duplicate indicator circuits was set by first throwing switch S_1 to the right to charge a condenser to 220 volts, and then to the left to connect the charged condenser to the tube circuit. Discharge of the condenser is prevented by a 22.5-volt negative bias on the grid. Switch S_2 was then thrown to the left to charge another condenser to 110 volts, and then to the right, discharging this condenser through the primary of the spark coil which produced the igniting spark. As each diaphragm made contact with its electrode, the grid bias was removed, and the 220 volt condenser discharged through the tube and through the spark coil which produced the recording spark for the indicator.

The various values of voltage, resistance, capacitance, and inductance given in the figure were found satisfactory, although considerable variation in most of these values is permissible. Either mercury- or argon-filled electron tubes may be used, short ionization time and adequate plate current (0.25 ampere or more) being the only requirements. By the use of condensers as the source of plate current, the tubes can be operated far above their rated steady current-carrying capacity, because the discharge of the condensers takes place in such a short time.

It was comparatively simple to make connections which allowed slight leakage from the high-tension ignition circuit to the grid circuits of the electron tubes. By such a device the firing spark was made to trigger the other two sparks. Photographs of the three sparks, taken under these conditions, show directly the time lag of the electron-tube circuits. Repeated observations revealed that the sparks in the tube circuits sometimes preceded the ignition spark by 15 microseconds and sometimes lagged behind it by the same amount. This variation seemed to be purely accidental in character and was probably due to effects at the spark gaps themselves. There seemed to be no evidence of a measurable lag in the tube circuits, and it is believed that the observed accidental variations were largely eliminated by

repetition of observations and by applying smoothing operations to the results.

Some difficulty was at first experienced with premature tripping of one or both tube circuits by leakage from a high-tension circuit. The 60-millihenry choke coil and the 0.002-microfarad condenser in the tube circuits were found to remove this difficulty. Shielding the grid circuits to obtain complete isolation of one from the other was also found desirable.

2. EFFECTS OF CONNECTING PASSAGES

In order to measure the effect of interposing connecting passages between the indicator and the explosion vessel, an indicator was

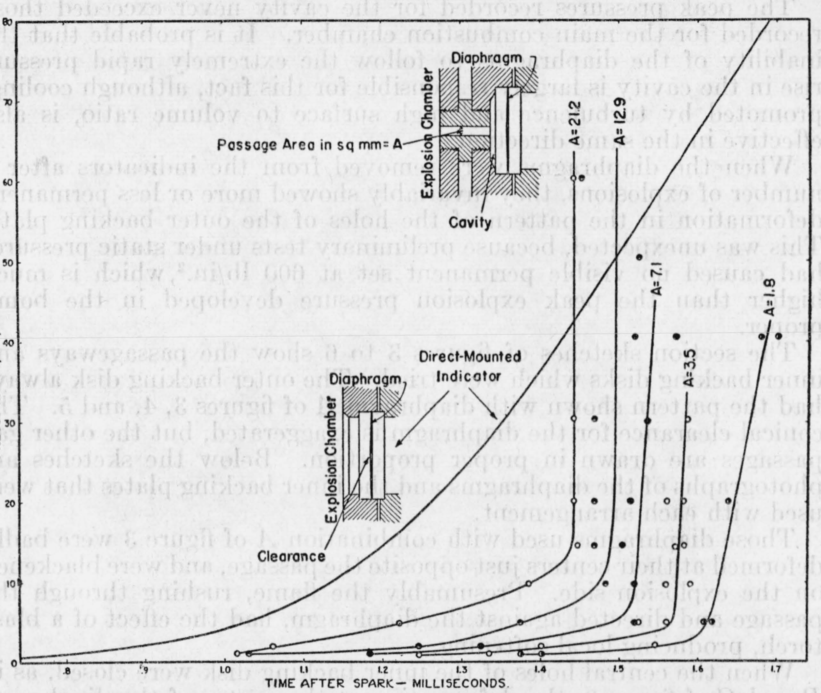

FIGURE 2.—*Effects of connecting passages upon the observed values of pressure.*

mounted directly on one end of the bomb and an identical indicator was connected through a passage to the other end. This is the arrangement illustrated in figure 1. The diaphragms themselves were 2⅛ in. in diameter and were cut from hard-rolled silver sheet about 0.0025 in. thick.

Time-pressure curves obtained with this combination of indicators for a comparatively fast-burning mixture of CO, H_2, and O_2 are shown in figure 2. The curve for the direct-mounted indicator is the result of a very large number of observations, not shown individually, from this and other series of observations. Comparable curves from the other indicator are shown for five different connecting passages, each 3.2 cm long and having the cross sectional areas shown in the figure.

The smaller the connecting passage the slower was the rate at which the pressure rose in the cavity at its outer end. This throttling

effect is to be expected as long as the pressure in the cavity is changed solely by flow of gas from the main combustion chamber. In such a cavity the pressure must lag behind that in the main combustion chamber by an amount which will increase as the passage is made smaller or longer, as the volume of the cavity is made greater, or as the rate-of-pressure rise in the bomb increases.

The sharp breaks in the curves for the passage-mounted indicator are doubtless caused by the occurrence, within the cavity, of secondary explosions, which are thereafter preponderant in effect upon the pressure at the diaphragm. The rapid rise in pressure from the secondary explosion is the natural result of igniting an explosive mixture which is initially in a highly compressed and turbulent state.

The peak pressures recorded for the cavity never exceeded those recorded for the main combustion chamber. It is probable that the inability of the diaphragms to follow the extremely rapid pressure rise in the cavity is largely responsible for this fact, although cooling, promoted by turbulence and high surface to volume ratio, is also effective in the same direction.

When the diaphragms were removed from the indicators after a number of explosions, they invariably showed more or less permanent deformation in the pattern of the holes of the outer backing plate. This was unexpected, because preliminary tests under static pressures had caused no visible permanent set at 600 lb/in.^{2}, which is much higher than the peak explosion pressure developed in the bomb proper.

The section sketches of figures 3 to 6 show the passageways and inner backing disks which were tried. The outer backing disk always had the pattern shown with diaphragm *A* of figures 3, 4, and 5. The conical clearance for the diaphragm is exaggerated, but the other gas passages are drawn in proper proportion. Below the sketches are photographs of the diaphragms and the inner backing plates that were used with each arrangement.

Those diaphragms used with combination *A* of figure 3 were badly deformed at their centers just opposite the passage, and were blackened on the explosion side. Presumably the flame, rushing through the passage and directed against the diaphragm, had the effect of a blast torch, producing local softening.

When the central holes of the inner backing disk were closed, as in *B* and *C* of figure 3, the deformation at the center of the diaphragm was greatly reduced. However, deformations in the pattern of the outer disk existed over the entire surface, and were accentuated when larger passages, as shown in *C*, were used.

For passage-mounted indicators the diaphragms never made contact with their electrodes at backing pressures exceeding 70 lb/in.^{2} It was therefore assumed that the deformations were produced only when backing pressures were low. Then the diaphragm is pressed against its outer support early in the explosion, and unburned charge is highly compressed in the conical clearance at the diaphragm before it is ignited. The resulting explosion in the conical clearance may therefore be much more violent than the secondary explosion in the larger cavity at the end of the passage. In fact, the appearance of the diaphragms furnishes definite evidence that the excessively high pressures are not developed in the main combustion chamber but in the cavities of the indicators.

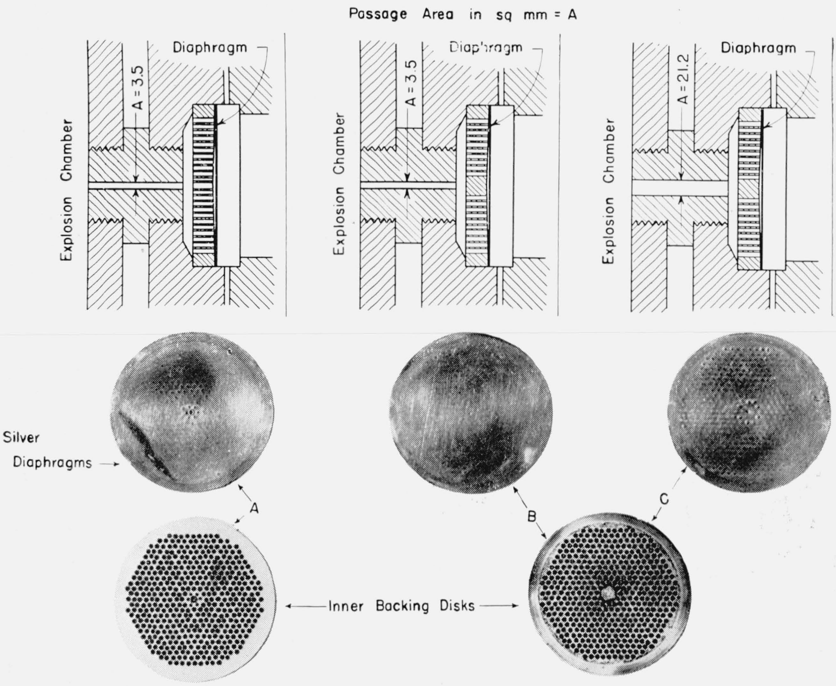

FIGURE 3.—*Deformations of silver diaphragms after use with two different connecting passages and two different inner backing disks.*

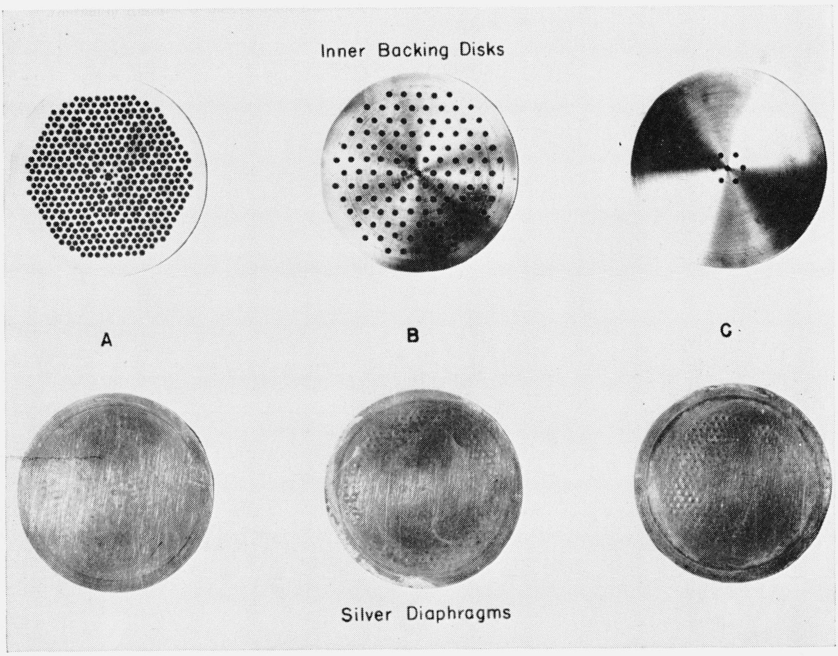

FIGURE 4.—*Deformations of silver diaphragms after use with three different inner backing disks, but without other connecting passages.*

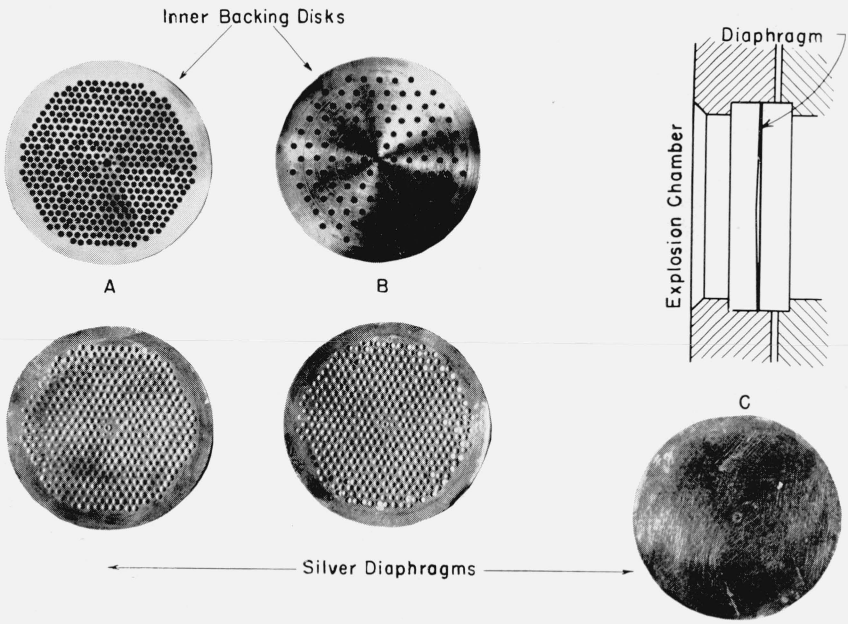

FIGURE 5.—*Extreme deformation of silver diaphragms, including partial rupture, resulting from very rapid burning in the clearance space.*

Diaphragm *C* shows the slight deformation produced by a static pressure of 750 lb per sq in.

3. EFFECTS OF BACKING DISKS

Figure 4 shows photographs of three diaphragms, with the corresponding inner backing disks, that were used in an indicator mounted directly on the end of the bomb. As previously stated, the outer backing disk was always of the type shown at *A*. When, as in case *A* the inner disk had many holes, interposing the least resistance between the combustion chamber and the clearance, the diaphragm was deformed least. If fewer holes were present, as in *B*, the deformations became more pronounced. When there were only seven holes, as in *C*, still greater deformation occurred, especially in that region of the diaphragm which was protected from the main explosion by the solid portion of the backing plate.

In one case the inner disk, *B*, was oriented so that each of its holes came directly opposite a hole in the outer backing disk. Practically no deformation of the diaphragm occurred when these outer holes were in line with like holes in the inner disk. However, there was considerable deformation into those holes in the outer disk which were opposite solid portions of the inner disk. This observation clearly indicates the existence of pressure differences of several hundred pounds per square inch within a millimeter or so of gaseous medium, and testifies to the extreme rapidity of the explosion in the clearance space. During the comparatively slow influx of the unburned gas, there is but little pressure drop in the passages of the inner backing disk. However, the more rapid burning of the heated and compressed gas in the clearance results in such a high rate-of-pressure rise that the pressure drop in the passages becomes very great.

In figure 5 (*A* and *B*) the effect of the explosions in the clearance is shown for a very fast-burning mixture of propane and oxygen. For comparative purposes, diaphragm *C*, which was subjected to a static pressure of 750 lb/in.^{2}, is included. Although the pressure developed in the explosion vessel by the burning of the propane mixture was probably not more than 200 lb/in.^{2}, the pressure in the cavity must have exceeded 1,000 lb/in.^{2} Diaphragms *A* and *B* show again that greater deformation results when the number of holes in the inner backing disk is reduced. In fact, a number of cleanly cut holes were produced near the rim of diaphragm *B*.

Deformation is usually greatest near the outer rim of the diaphragm. This is probably because the gas in this region, being the last to burn, is more highly compressed before it is ignited, and therefore produces the maximum pressure upon burning.

A number of tests were made to determine whether the inner backing plate had sufficient throttling effect to cause a lag similar to that shown in figure 2 for connecting passages. While the effect of thin, well-perforated backing plates is probably so small as to be negligible for most practical purposes, the tests indicated that the presence of a backing plate does produce a lag detectable with the precise methods of recording employed. The amount of error appears to increase (1) as the number of holes in the disk is reduced, (2) as the thickness of the disk is increased, and (3) as the distance which the diaphragm moves is made greater.

4. EFFECTS OF BACKING PRESSURES

Deformation of the diaphragms was apparently due to secondary explosions of great force, but involving only a very small amount of gas, in the clearance of the indicator. Despite this fact, the indicators never recorded pressures higher than those which would be expected from the primary explosion in the main combustion chamber. It was therefore logical to believe that the application of high backing pressures would hold the diaphragm against its inner support and prevent the explosive charge from entering the clearance, where it could be involved in a secondary explosion.

To test this theory, a backing pressure of 165 lb/in.^{2} was applied and the diaphragm examined after a single explosion. Its photograph appears at *A* in figure 6. Even though the indicator did not record, the diaphragm showed distinct deformation into the perforations of both the inner and the outer backing disks. An interpretation which seems to fit the observed facts is that a very rapid burning, probably a detonation, in the large cavity at the end of the passage and in the holes of the inner backing plate drove the diaphragm against its outer support with great suddenness and violence, except for a small area at the center which failed to touch the electrode. The failure to make electric contact and the reverse dimple at the center of the diaphragm were probably due in part to the fact that the solid portion at the center of the inner backing plate prevented the full force of the detonation in the cavity from reaching the center of the diaphragm. In addition, the electrode itself and the small holes surrounding it apparently offered sufficient resistance to the escape of the gas in the backing-pressure chamber to hold a gas pocket around the electrode.

After producing the small ring of deep dents around the center of the diaphragm and the shallower dents over the area near the rim, the explosion pressures must have collapsed as suddenly as they were developed, allowing the diaphragm to be slapped back against its inner supporting disk by the backing pressure with sufficient suddenness to produce deformation in the opposite direction. These deformations into the holes of the disk on the explosion side (shown on the photograph by the light spots in the area beyond the small ring of deep dents) are evidence of the suddenness and completeness of the collapse of the explosion pressure, for they could have been produced only by violent impact of the diaphragm with the inner disk following tremendous acceleration across the clearance of only a few thousandths of an inch. Although the backing pressure of 165 lb/in.^{2} might produce such an acceleration if the pressure on the explosion side were very low, it would be entirely inadequate to produce the observed deformations in the absence of violent impact.

With the same indicator and passage, a diaphragm was subjected to the low backing pressure of 1 lb/in.^{2} and removed after a single explosion (diaphragm *B*, fig. 6). As expected, it shows the effect of the violent explosion within the clearance, being more deeply deformed by the outer backing disk and by the electrode than was diaphragm *A*, because of the better opportunity for compression of gas into the clearance space. Diaphragm *B* shows deformation into only the outer backing plate and has a different general appearance from diaphragm *A*, demonstrating that the character of the explosion in the clearance is affected by the backing pressure.

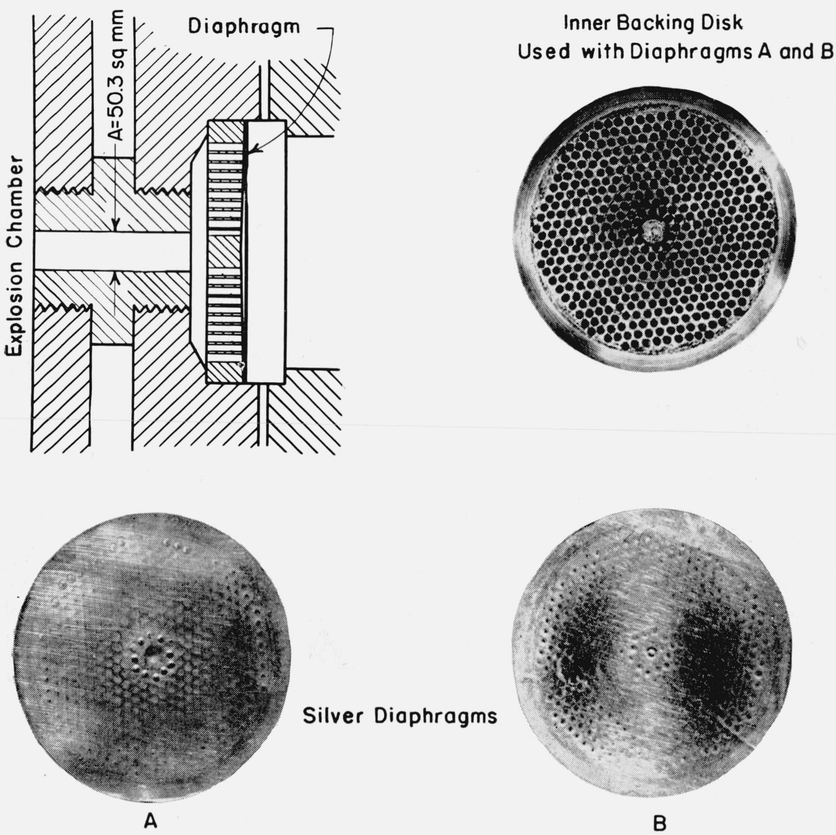

FIGURE 6.—*Differences in deformation after one explosion using a high backing pressure (diaphragm A) and one using a very low backing pressure (diaphragm B).*

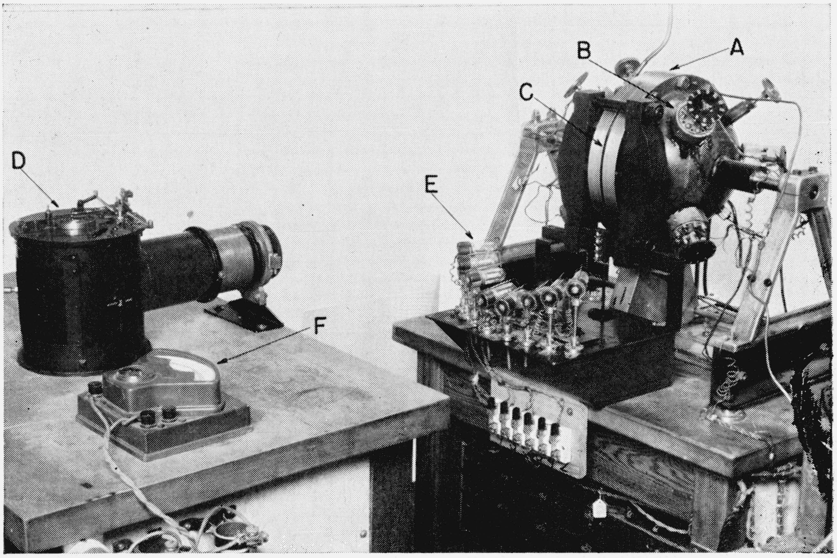

FIGURE 7.—*General view of spherical bomb and accessories.*

A, the bomb; *B*, a pressure indicator; *C*, the window slit; *D*, the camera; *E*, the neon lamps; and *F*, the electric tachometer

Detailed conclusions from the foregoing experiments with indicators having soft diaphragms are given at the end of this paper. However, all of the results obtained with passages and inner backing disks show that such restrictions are undesirable in an indicator designed for highest accuracy. Hence the diaphragms of the indicators which were finally evolved for studies of the burning process were directly exposed, over their entire effective area, to the explosive mixture.

Since the spherical bomb which was built for the combustion studies became available at this stage in the development, it was used for a further examination of the characteristics of the indicators because it accommodated six of these instead of two.

III. EXPERIMENTS WITH INDICATORS ON A SPHERICAL BOMB

1. APPARATUS

The spherical bomb and accessory apparatus, as illustrated in figure 7, have already been described in the paper referred to in footnote 1. Briefly, the bomb was a 10-in. sphere having central ignition, a window through which the progress of the flame could be photographed, and six openings through which the pressure indicators could be attached.

The details of a pressure indicator and its recording circuit are shown in figure 8. The spring-steel diaphragm, D, is clamped between the two brass body parts, C_1 and C_2, through the right- and left-hand threaded band, B. The electrode, E, is threaded (¼ in., 48) through the lower part of the gland, G, and sealed against leaks by paraffined leather packing, P, above the thread. Gland G, and hence also the electrode, is insulated from the remainder of the indicator by the mica washers, M, and an air space. That part of the electrode above the packing is threaded to accommodate the lock nut, N, which insures against accidental movement of the electrode between setting and firing, and the bakelite wheel, W, which is divided into 120 equal parts at its circumference to provide for measuring the sensitivity of the indicator. The stainless-steel contact, F, on the lower end of the electrode is slightly conical, with the vertex of the cone toward the center of the diaphragm. This contact serves to support the diaphragm over most of its area after the contact is made and to remove heat after the arrival of the flame. The ring, R, behind the diaphragm fixes the effective diameter. The pressure in the space behind the diaphragm could be controlled through the tube, T. All parts are made of brass except those already specified.

Each indicator is attached to the bomb by eight stud bolts which pass through holes, H, in the indicator. By means of appropriate steel sleeves, S, the force holding the indicator against the bomb is applied to body part C_1 only. Undesirable distortions of other parts of the indicators are thus avoided. The seal to the bomb is made by placing a thin gasket of soft aluminum between a flat surface on the bomb and the V-shaped bead on C_1.

When the indicators were assembled at room temperature, the thinner diaphragms were seldom flat. It was found that this wrinkling could be avoided by introducing a high initial radial tension in the diaphragm. To provide such tension, the indicators, while assembled loosely, were surrounded with dry ice. With the body of the indicator thus cooled, the flat end of a metal cylinder heated to

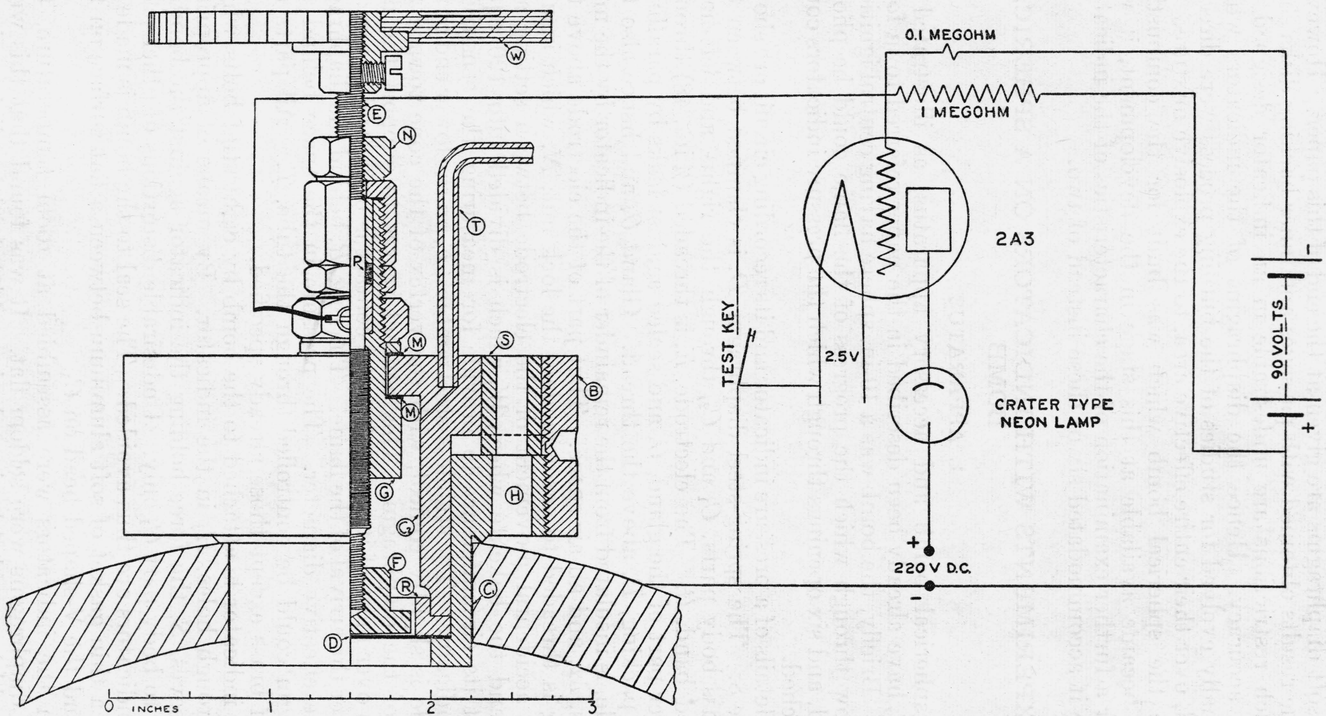

FIGURE 8.—*Indicator and wiring diagram for neon lamps used with the spherical bomb.*

the melting point of tin, was held firmly against the exposed face of the diaphragm, the band was tightened, and the hot diaphragm was clamped in the cold brass. Upon returning to room temperature, the spring steel cooled and shrank, while its clamping rings warmed and expanded, leaving the diaphragm taut and flat. Some slippage of the steel relative to the brass is thought to have occurred, since the sensitivities of indicators with identical diaphragms were so nearly alike after this treatment, although the temperatures of the parts at the time of assembly were not closely controlled.

The arrangement used for obtaining a photographic record of the instant at which the diaphragm made contact with its insulated electrode is also shown in figure 8. Briefly, contact between diaphragm and electrode removes the negative bias on the grid of a vacuum tube (2A3) acting as a relay, permitting the plate current to flow through a crater-type neon lamp. This circuit was found to have a negligible time lag, and, with a very small current passing through the indicator contact, no difficulties with fouling or pitting of the contact have been experienced.

Light from the neon lamp shines through a pinhole onto a mirror which reflects it into the lens of a camera. It is focused, through a shutter and fixed slit, upon a film, where a line image is left as the film revolves. The origin of this line, which is sharp and readily measurable, shows when the explosion pressure has reached the value for which the indicator was set under static conditions.

2. PROCEDURE

The main steps in the procedure during these test experiments, which were the same as those followed in the normal recording of an explosion (footnote 1), were as follows. The temperature of the bomb was controlled at 25° C, the backing pressure was adjusted, the indicators were set, the bomb was evacuated, explosive mixture was admitted to a pressure of 1 atmosphere, and the charge was fired upon opening the camera shutter. Such departures as were necessary are described in sections dealing with particular tests. Since the purpose of these experiments was to determine comparative effects of various constructional differences among the indicators, all six were set to record the same pressure in any single explosion.

For such comparative tests the flame records are not required. Hence the film speed could be increased approximately twofold, to a value which, although it gave an underexposed flame trace, was still satisfactory as far as the exposure of the time and pressure records was concerned.

3. TEMPERATURE OF THE INDICATORS

Since the coefficient of thermal expansion of the brass clamping rings is greater than that of the steel diaphragms, the indicators are sensitive to changes in temperature. To minimize the error from this source, the temperature of the room in which the bomb was used was carefully regulated. In most of the tests reported here the temperature of the bomb was within $\pm 0.1°$ of 25° C, and changes in temperature between setting the indicators and firing the charge seldom exceeded 0.01° C. Such control effectively eliminated errors which certainly would have arisen in its absence.

4. LAG IN THE RECORDING SYSTEM

The lag in the neon-lamp circuits was determined by photographing the firing spark and the neon lights when electrical leakage from the former was allowed to trigger the lamp circuits. All of the lamps lighted within 13 microseconds after the first spark. On the explosion records this time interval represents, on the average, a distance of only 0.1 mm, which is also the limit of precision in the measured distances on the film. The time lag in the electric circuits for the indicators may, therefore, be justly neglected. When only an intercomparison of the indicators is sought, such lag is of even less consequence, since its variation for the six independent lamp circuits is only a fraction of the 13 microseconds.

5. PITTING AT THE CONTACT BETWEEN DIAPHRAGM AND ELECTRODE

Experience has shown that, for the particular electric circuits employed, the electric contact between the blued-steel diaphragm and the stainless-steel electrode is highly reproducible. Pits at the point of contact do become visible after continued use, but these are formed at a negligible rate.

In the use of the indicators, it was found desirable to rotate the electrode in contact with the diaphragm prior to taking each measurement. Such a procedure may have moved aside some tiny particles which, if let alone, might have decreased the reproducibility of the contact.

Another seemingly desirable, but possibly unnecessary, precaution against pitting was taken by opening the lamp circuits externally, instead of at the diaphragm, after they had been closed by the application of static pressure.

6. INERTIA OF THE DIAPHRAGM

Perhaps the most obvious and troublesome source of possible error arises from the fact that, for a given pressure difference, the position of the diaphragm will vary with the rate at which pressure is applied. In other words, when the diaphragm is subjected to a rapidly rising pressure, some small part of this pressure is required to impart motion to the diaphragm, and it is therefore deflected less than it would be if an identical but constant pressure difference were maintained on its two sides. Thus, when the position of the diaphragm is used as an index of this pressure difference, and when the indicator is calibrated or set with an essentially static pressure, it should not be assumed without further verification that, at the instant the same position is attained during a rapid rise in pressure, the instantaneous value of the rising pressure is identical with the static pressure at which the indicator was set to record. It will be shown, however, that this assumption can be justified for an indicator properly designed for a specific purpose, or more specifically that the error from this source, which is hereafter termed briefly the inertia of the diaphragm, can be reduced to a value within the allowable tolerance.

Obviously, if it is desired to measure pressures to the nearest 0.1 mm Hg, this increment of pressure must change the position of the center of the diaphragm by a detectable amount. In other words, the assignment of an arbitrarily chosen tolerance in pressure at once determines the minimum usable sensitivity of the diaphragm and the

device used for determining its position. The term "sensitivity" is used to denote the deflection per unit pressure difference, which is the slope of the experimental pressure-deflection curve.

It is also apparent that the error due to inertia of the diaphragm can be reduced by decreasing its effective mass and its sensitivity. However, if the mass is made less by using a thinner diaphragm, the effective diameter must also be decreased to avoid an increase in sensitivity. The sensitivity of a diaphragm of a given thickness and effective diameter can be further reduced by the introduction of radial tension.

Thus it is concluded that the less the effective mass and diameter and the greater the stiffness, the more nearly will a diaphragm assume the same position when an identical pressure difference is applied statically and dynamically. The practical limit to these characteristics is fixed by the previously selected minimum sensitivity to pressure difference. It is therefore necessary, in designing an indicator for rapidly changing pressures, to adopt that compromise between sensitivity and inertia which seems most satisfactory for the intended specific application of the instrument. To satisfy this requirement, the component parts of the indicator as a whole must have the following characteristics: (1) In an attempt to gain sensitivity, the thickness of the diaphragm must not be reduced to a value which allows permanent deformation under the service conditions. (2) The sensitivity to pressure difference must exceed a minimum value determined by the accuracy with which pressures are to be measured. (3) The sensitivity of the diaphragm must be reduced as far as possible to insure that the inertia error is kept within the allowable tolerance.

It will be shown that the pressure indicators which have been described, when fitted with spring-steel diaphragms 0.002 in. thick and $1\frac{3}{16}$ in. in effective diameter, under high initial radial tension, do satisfy these requirements to a degree which permits the measurement of explosion pressures with an accuracy of a few tenths of 1 mm Hg. Such high accuracy in the observed values of pressure is necessary, particularly in the early stages of the explosions, if reliable values of the burning characteristics are to be derived from the directly observed time-pressure and time-displacement records. It is fortunate that, for this purpose, less accurate values of pressure suffice later in the burning process, when the rate of rise in pressure has become exceedingly high.

Although many materials available in thin sheets are somewhat less dense than clock-spring steel, the latter is superior as a material for diaphragms in explosion studies because of its high elastic limit and the persistence of this limit after exposure to flame. There is now some reason to believe that a copper-beryllium alloy, which was not available when these studies were undertaken, will prove equally satisfactory for the purpose. However only spring-steel diaphragms, varying in thickness from 0.001 in. upward, were used in the present survey.

7. EFFECTS OF DIAPHRAGM DIMENSIONS

Not only was it difficult to assemble an indicator so that a 0.001-in. diaphragm would remain flat, but also such diaphragms were rather severely distorted by the flames and had to be replaced after a very limited number of explosions. These limitations indicated that it

was highly desirable to use thicker diaphragms, if it were at all practicable.

Wrinkling of the diaphragms could be avoided by the process of assembly when the thickness was 0.002 in., and was practically nonexistent for still thicker disks. When the 0.002-in. diaphragms were supported and cooled by the electrode during the period of exposure to flame, the distortion also became a negligible factor and it was not

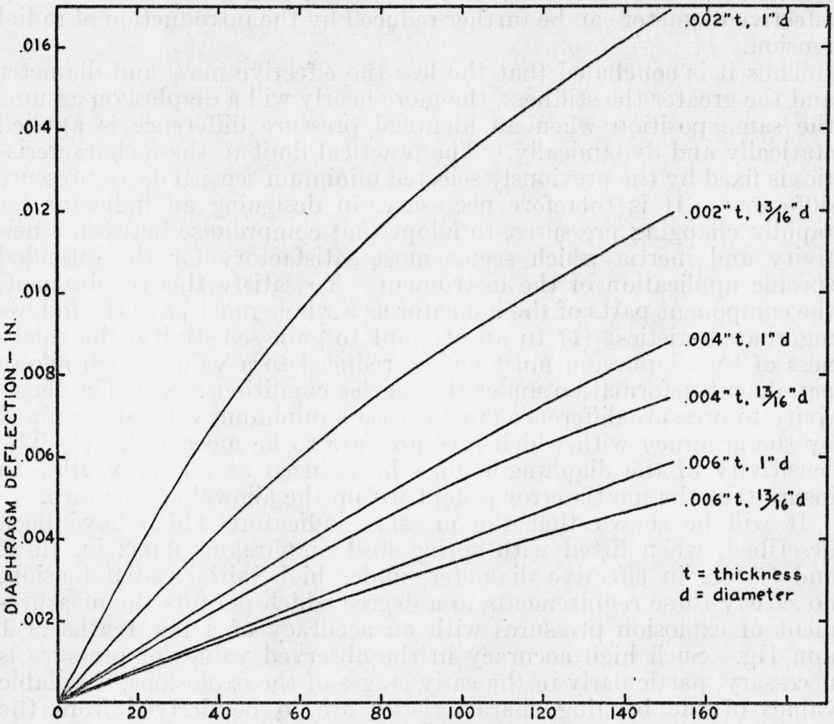

FIGURE 9.—*Pressure-deflection curves for diaphragms of different dimensions.*

necessary to replace a single diaphragm over a period of several months of regular use.

Having proved the ability of the 0.002-in. diaphragms to withstand the service conditions, it became necessary to determine the minimum diameter which such a disk could have and still be adequately sensitive to a pressure difference of 0.1 mm Hg. For this purpose a number of curves, of which those shown in figure 9 are typical, were obtained. Here the relations between static pressure difference and amount of deflection are plotted for diaphragms of three different thicknesses and two different diameters. The slopes of these curves are the sensitivities of the diaphragms. In each case there was present an unknown amount of initial tension, believed to be limited by frictional resistance to slippage between the steel disk and its brass clamping rings.

Since it was planned to set the indicators by application of static pressure prior to each explosion, it was not necessary that the diaphragm should deflect in direct proportion to pressure. In fact, as

already pointed out, a decreasing sensitivity with increasing pressure was quite permissible.

The sensitivity of the 0.002- by 13/16-in. diaphragm was sufficiently great to permit ready detection of pressure changes of 0.1 mm Hg over the entire range shown in figure 9. The same was, of course, true for all values of diameter greater than 13/16 in. However, when the diameter was made less than this, it was no longer possible to make successive readings of static pressure for a given indicator setting which were consistently within ± 0.1 mm Hg of the mean, nor could this precision be attained with the 0.004- by 1-in. diaphragm. Thus, from the standpoint of sensitivity and ability to withstand the service conditions, the limits 0.002 by 13/16 in. seemed to represent the practical minima to which these dimensions could be reduced.

It may at first seem doubtful, as it did to the authors, that the simple mechanism of the threaded electrodes could be used to measure

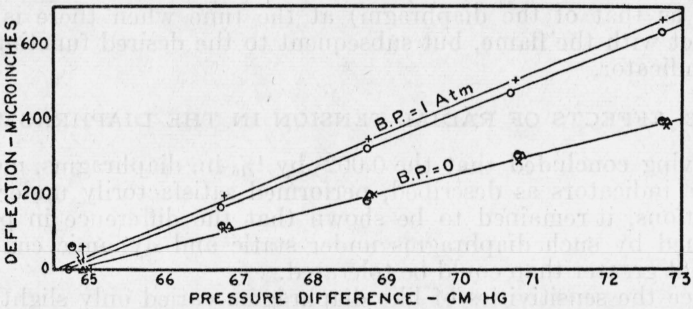

FIGURE 10.—*Highly enlarged section of pressure-deflection curve for one diaphragm, showing the lower sensitivity with evacuated backing space, and the reproducibility after successive explosions.*

the positions of the diaphragms under static pressure differences with the necessary accuracy, and that the position assumed by the diaphragm under successive applications of the same static pressure would be reproducible within the same small tolerance. Such fears, however, have been proved groundless by many data of the type presented in figure 10. This figure is essentially a highly magnified section of the curve in figure 9 for an indicator with a 0.002- by 13/16-in. diaphragm. Figure 10 shows five sets of experimental pressure-deflection data for a limited pressure range and for one indicator.

Between successive calibrations the diaphragm was in direct contact with flame and with burned gas during an explosion in the bomb. The two curves having the greater slopes were taken with atmospheric pressure in the backing space of the indicator, and the crosses, triangles, and shaded circles represent three calibrations with this space evacuated.

The indicating wheel on the electrode stem was divided at its circumference into 120 equal spaces, each 0.067 in. wide, so that the position of the wheel relative to a fixed pointer could be read by an experienced observer to the nearest 0.05 of a division. With 48 threads per inch on the stem of the electrode, 0.05 of a wheel division corresponds to an axial movement of the electrode of about 9 microinches. The fact that successive calibration points seldom deviate

by more than this amount from a smooth curve strengthens the belief that the errors in determining diaphragm position were usually within this tolerance.

It is believed that uncertainties which might have arisen from backlash were avoided by careful lapping of the threads and by the packing through which the stem of the electrode passed. This packing, which consisted of washers of leather impregnated with paraffin, was always under considerable hydrostatic pressure and hence offered a constant frictional resistance to all movements of the stem.

The data of figure 10, as well as those of many similar charts for other indicators at other parts of the pressure curve, also show that the performance of the diaphragm is not altered appreciably by successive exposures to flame. Experience shows that such reproducibility cannot be expected unless the diaphragms are in good thermal contact with a body of relatively high heat capacity (in the present case the slightly tapered electrode, with an area nearly as great as that of the diaphragm) at the time when there is direct contact with the flame, but subsequent to the desired functioning of the indicator.

8. EFFECTS OF RADIAL TENSION IN THE DIAPHRAGMS

Having concluded that the 0.002- by 1$\frac{3}{16}$-in. diaphragms, mounted in the indicators as described, performed satisfactorily under static conditions, it remained to be shown that the difference in position assumed by such diaphragms under static and dynamic conditions was not greater than could be tolerated.

Since the sensitivities of like diaphragms varied only slightly, the tension introduced in the flat diaphragms by the process of assembly must have been nearly uniform for all indicators. However, since the amount of deflection of the diaphragms was not directly proportional to pressure, and since the pressure in the backing space could be varied at will, an opportunity for studying the effect of sensitivity upon the performance of the indicators when subjected to rapidly rising pressure was provided. Thus, if the backing space was evacuated, the diaphragm had a large amount of initial deflection and was least sensitive. If the backing space was open to the atmosphere, the sensitivity to the same pressure change was increased. If a balancing pressure was maintained in the backing space, the diaphragm made contact with the electrode at the neutral or undeflected position of the former, which is the condition for maximum sensitivity. The results presented in figures 11 and 12 are typical of the way in which the sensitivity of the diaphragm influences its performance under the conditions prevailing during an explosion.

The results shown in figure 11 were obtained with five different indicators, each set to record when the pressure had increased by 69.00 cm Hg during five successive explosions. Prior to each of the five explosions the sensitivities at Δp=69.00 cm Hg were determined from plots of the observations similar to figure 10. For 12 of the 25 recorded values of pressure the backing space was evacuated, and for the other 13 the known pressure of the atmosphere was admitted to this space. As shown in the figure, the average sensitivity in the former set was approximately half as great as that in the latter.

One of the indicators was used with atmospheric backing pressure in all five explosions, and the pressure record from this indicator served in each case as a purely arbitrary zero of time, from which differences in the time of recording of the other indicators were measured. The deviations of those indicators recording after the reference indicator are arbitrarily called positive in figure 11.

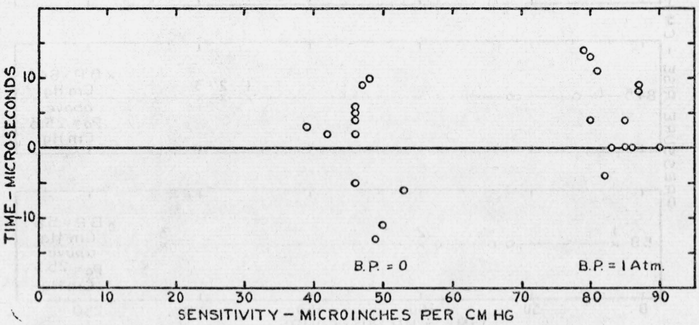

FIGURE 11.—*The negligible effect upon the time of recording produced by halving the sensitivity through evacuation of the backing space.*

Two conclusions of importance are apparent from this figure. First, the effect of changing the sensitivity by a factor of nearly 2 is so slight that it is entirely obscured by the accidental spread of the results. Second, the accidental deviation from the mean is less than 10 microseconds, which is in turn within the error of measurement of distance upon the actual explosion records. In fact, the spread shown in figure 11 is of the same order of magnitude as that previously observed in the earlier measurements of the time lag of the electric circuits. So far as the performance of the indicators is concerned, there thus seems to be little choice between having the backing space evacuated or having it open to the atmosphere. Practically, however, it is easier to maintain a vacuum than any other constant pressure in the backing spaces.

The results presented in figure 12 show the comparative effects of using the diaphragms distended by evacuation of the backing space or flat at the instant of contact as a result of a balancing pressure. These data were obtained with a preliminary form of indicators and before the final refinements in temperature control were adopted. Although some spread in the observations was doubtless produced by small changes in temperature, nevertheless the results furnish convincing evidence in favor of using low pressure in the backing space.

The sensitivities of the indicators whose results are represented by the crosses in figure 12 were from four to eight times as great as those for which the circles are used. It is at once apparent that the more sensitive indicators, set to record the same pressure, make contact later and that the spread is greater on the average for such diaphragms. The separate strips are for three different values of pressure rise and two different values of initial pressure (p_0).

Since the sensitivity of the evacuated indicators was adequate, and since such indicators show less accidental spread and earlier contact than those with a balancing pressure, the former are preferable for the present purpose.

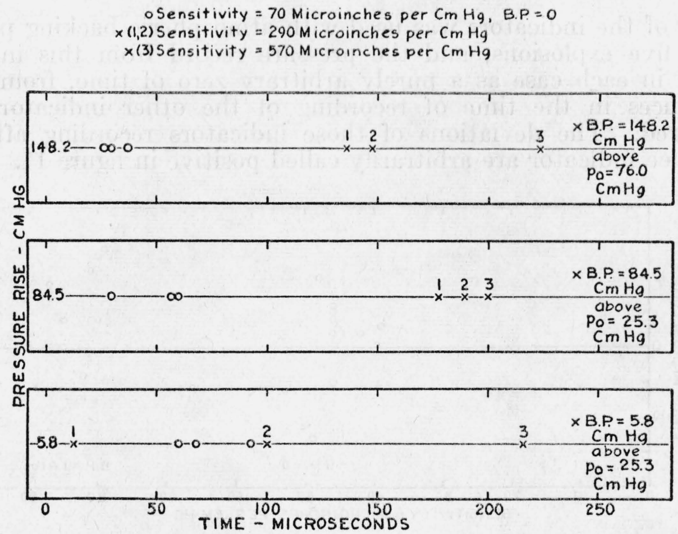

FIGURE 12.—*The comparatively large time lags in the recording of the indicators, as produced when the sensitivities were increased from four to eight times by employing balancing pressures.*

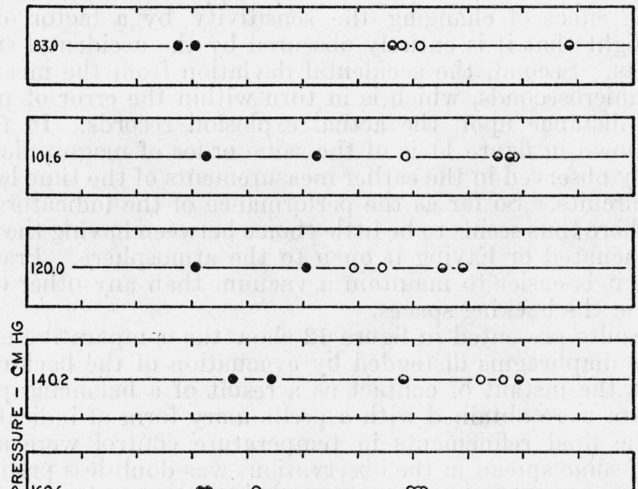

FIGURE 13.—*The effects of absorbed radiant energy upon the time of recording of the indicators.*

9. EFFECTS OF SURFACE CONDITION OF THE DIAPHRAGMS

In order to observe the effects of the absorption of radiant energy during the combustion period upon the performance of the indicator, the inner surfaces of two of the diaphragms were painted with optical black, two were polished, and the other two were left with blued finish.

The results obtained in seven different explosions, all six indicators being set to record the same pressure in each, are shown in figure 13. Without exception the diaphragms whose surfaces were painted black recorded earlier by about 40 microseconds on the average. However, there is no consistent difference in the time of recording of the blued and polished diaphragms. It is therefore concluded that the blued surface is as satisfactory as the polished one from the standpoint of absorption, and it is preferable because it does not rust so readily.

10. EFFECTS OF PROJECTIONS INTO THE BOMB AROUND THE DIAPHRAGMS

During the evolution of the indicators toward the final form shown in figure 8, one set of these was built with steel bodies and with 0.002-in.-thick diaphragms soldered directly to the bodies. In the neutral

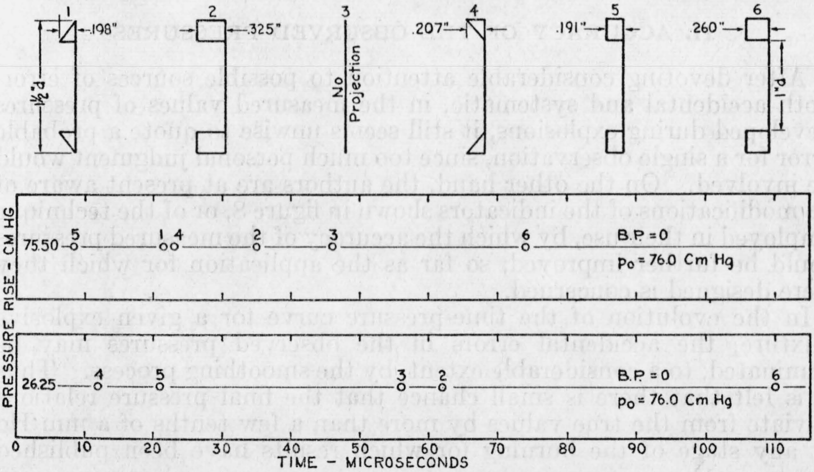

FIGURE 14.—*Effects of projections around the diaphragm upon the time of recording.*

position none of the soldered diaphragms was entirely flat. However, with the backing spaces evacuated the indicators operated fairly well, but showed an accidental spread considerably greater than did the final modification. Part of this spread was due also to inadequate control of temperature. These instruments, having no projections into the bomb beyond the diaphragms, provided an opportunity for studying the effects of such projections. For this purpose five rings, having the dimensions shown at the top of figure 14, were attached to the explosion side of the diaphragms, whence they projected into the bomb when the indicators were mounted, while the diaphragm of No. 3 was left without any projection.

With all indicators set to record the same pressure, with the backing spaces evacuated, and with an initial pressure (p_0) of 76.00 cm Hg, the results obtained for an observed rise in pressure of 75.50 and of 26.25 cm Hg are shown in the two strips of figure 14. In both cases the values of time, as shown, are reckoned from an arbitrary zero to avoid the use of the large numbers which would be necessary if the instant of firing were taken as the zero. The numbers of the observed points correspond to those assigned above to the projections. Indicator 1 failed to record in the run at 26.25 cm Hg for some unknown reason.

An examination of the results presented in figure 14 shows a random distribution of the observations made with the projections, about those of the indicator having none. Likewise, there is apparent no progressive effect of increasing the length of the cylindrical projections—that is, the indicator having the longest projection (No. 2) records, in both cases, at a time intermediate between those having shorter projections (Nos. 5 and 6). It was therefore concluded that the effects of the projections tried were less than the accidental spread of the observations, and that such effects could be neglected, at least for the early stages of the burning, during which the most accurate measurement of pressures was required. Projections having the same dimensions as No. 5 of figure 14, were used on the final indicators.

11. ACCURACY OF THE OBSERVED PRESSURES

After devoting considerable attention to possible sources of error, both accidental and systematic, in the measured values of pressures developed during explosions, it still seems unwise to quote a probable error for a single observation, since too much personal judgment would be involved. On the other hand, the authors are at present aware of no modifications of the indicators shown in figure 8, or of the technique employed in their use, by which the accuracy of the measured pressures could be further improved, so far as the application for which they were designed is concerned.

In the evolution of the time-pressure curve for a given explosive mixture, the accidental errors in the observed pressures may be eliminated, to a considerable extent, by the smoothing process. Thus it is felt that there is small chance that the final pressure relations deviate from the true values by more than a few tenths of a mm Hg at any stage of the burning for which results have been published (footnote 1).

IV. CONCLUSION

As a result of many test experiments, an indicator has been developed for the accurate measurement of the rise in pressure produced by the normal burning of a gaseous explosive mixture in a bomb. The following conclusions, which may prove useful in designing indicators for other specific purposes, have been drawn from studies of the performance of special types of indicators used in the present development work and of the indicators finally evolved for use with a spherical bomb. Although some of these conclusions are not original, all are supported by the experimental evidence that has been presented.

Any constriction between the explosion chamber and the diaphragm of a pressure indicator should be avoided when high accuracy is required, particularly when fast-burning mixtures are exploded. The compressed gases should have unimpeded access to the diaphragm, which for best results should form a part of the combustion chamber wall. If restrictions are unavoidable, they should present minimum resistance to gas flow—that is, passages should be large and short, and backing plates should be thin and well perforated. The volume at the end of any passage should also be reduced to a minimum.

The error due to a passage increases with the rate of rise in pressure, and hence also as the burning progresses. The error due to a thin, well-perforated backing plate is likely to be negligible for most purposes during the period of normal burning.

For explosive mixtures which tend to detonate or to burn with extreme rapidity, the presence of a restriction between the combustion chamber and the diaphragm is apt to cause abnormally high, and perhaps destructive, local pressures at the diaphragm. Such local pressures may exceed the maximum attained in the combustion chamber proper, and the indicated pressures may not apply at all to this chamber . Although the diaphragm cannot be relied upon to indicate these abnormally high pressures accurately, a qualitative idea of their magnitude may be obtained by observing the deformation produced in relatively soft diaphragms.

An indicator capable of yielding values of pressure, with an accuracy of a few tenths of 1 mm Hg, during normal explosions, should have the following characteristics: The diaphragm should not be permanently deformed under the service conditions. The sensitivity to pressure difference must exceed a minimum value determined by the accuracy with which the pressures are to be measured. The sensitivity of the diaphragm must be reduced as far as possible to insure that the inertia error is kept within the allowable tolerance. The pressure indicators described, when fitted with spring-steel diaphragms 0.002 in. thick and 1$\frac{3}{16}$ in. in effective diameter, under high initial radial tension, satisfy the above requirements.

The results of a series of tests designed to evaluate the pressure error which might be expected from various sources in the use of such an indicator may be summarized as follows: (a) The time lag in neither of two electric systems used to convert an impulse from an indicator into a signal which could be photographed is greater than the accidental error in the measurement of distance on the film. (b) Diaphragms under high radial tension respond more rapidly to changes in pressure than those without such tension. In other words, of two indicators having diaphragms of identical thickness and sensitivity, the one having the larger diameter but considerable radial tension is the more reliable. (c) The effect of increasing the sensitivity of a given diaphragm to nearly twice the allowable minimum is entirely obscured by the accidental spread of the results, which is also within the error in the measurement of distance on the film. On the other hand, diaphragms with from four to eight times the minimum sensitivity record slightly late. (d) Diaphragms having blued surfaces record simultaneously with those which are polished, but when the inner surface is made highly absorbing, by a coat of optical black, a slightly earlier recording is caused by the absorption of radiant energy. (e) Various annular projections into the bomb around the

diaphragms produce no systematic effects which can be distinguished from the accidental spread of the observations. (f) Thinner diaphragms than would otherwise be practicable may be used if the electrode is large so that it supports the diaphragm after contact is made and removes heat after the arrival of flame. (g) The indicators are sensitive to changes in temperature, but when these are avoided, contact is made within 0.1 mm Hg of the same static pressure upon repeated trials.

It seems probable that the effects of accidental errors in the single observations can be decreased to some extent by smoothing operations applied to the data. Among the systematic errors, that resulting from inertia of the diaphragms is probably in the direction of low observed pressures, and that due to lag in the recording circuits is certainly in this same direction. However, that resulting from the absorption of radiant energy by the diaphragms is in the opposite direction. All things considered, it is felt that there is small chance that the final, smoothed pressure relations deviate from the true values by more than a few tenths of 1 mm Hg at any stage of the burning for which results have been published.

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